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Abundance Anomalies Produced by Nuclear Reactions in Stellar Surface Layers. II. Results and Comparison with Anomalies in Peculiar A Stars

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Abstract

A normal solar abundance distribution of the elements was subjected to a calculated bombardment by protons and alpha-particles having energy spectra of the form E^{-n}, where n was usually taken to be equal to 2.5, and with a low energy cutoff on the spectrum at 1 MeV. Bombardment with protons resulted in break-down of nuclei toward lower mass numbers. Bombardment with alpha-particles resulted in build-up of nuclei toward higher mass numbers. It is concluded that preferential acceleration of alpha-particles to varying total fluxes can produce the abundance anomalies of peculiar A stars in concentrated patches on the surface. Local surface magnetic fields in the range 10^6 - 10^7 gauss are required to provide the necessary energy sources for the accelerated particles.

Introduction

The peculiar A stars present one of the more puzzling problems of astrophysics. These stars are characterized by the existence of strong variable magnetic fields coupled with what appear to be large overabundances of certain elements. These anomalous abundances are of particular interest because they suggest that the evolutionary histories and/or the surface conditions of these stars have been rather unusual.

Average magnetic fields on peculiar A stars are typically on the order of 10^3 to 10^4 gauss; the field variations are irregular for some stars and periodic for others, with periods as short as 8 d (Babcock, 1958). The most likely explanation for these variations is given by the oblique rotator model, in which it is assumed that the magnetic axis of the star is inclined to the axis of rotation and both are inclined to the line of sight.

A typical A star has a surface temperature on the order of 10^4 ^oK, and a density of 10^{15} atoms/cm^3 in the photosphere. Such stars would be expected to have shallow convection zones, and the existence of a magnetic field would tend to further inhibit convection. The Ap stars have essentially these same properties. They are found near the main sequence, but are slightly more luminous than normal A stars. Their distribution in the galaxy is no different from that of normal A stars. Their spectra are peculiar in two ways: besides the abnormal strengths of certain spectral lines, there are also variations in the intensities of these lines, often correlated with the variations of the magnetic field.

The abundance anomalies have been summarized by Sargent (1964) and Fowler, Burbidge, Burbidge and Hoyle (1965). Table 1 has been taken from Sargent; it lists the logarithmic overabundances (as compared to normal A stars) observed for several well-known Ap stars. We can make some general statements as to the most notable abundance anomalies, keeping in mind that no element exhibits the same anomaly in all Ap stars.

The lightest elements such as He and O are generally underabundant by factors of about 10. Si is overabundant by about 10 in the hotter Ap stars, but is less so in others. Ca is often underabundant by 10-100. The elements in the vicinity of iron - Ti, V, Cr, and Mn - are usually overabundant, particularly Mn in the hotter stars and Cr in the cooler ones. Fe is normal or slightly overabundant.

Ga and Kr have been found to be overabundant by a factor of 1000 in 3 Cen A. The elements Sr, Y, and Zr are overabundant in most Ap stars by 10-100. The most prominent overabundances, however, are found for the rare earth elements La, Ce, Pr, Nd, Sm, Eu, Gd, and Dy: these are not seen at all in normal A stars, but they have an average overabundance factor of about 500 in Ap stars. Moreover, Ba, which is the last element before the rare earth group, is usually normal or slightly overabundant.

To conclude the survey, we note that an overabundance of Hg in the star K Cnc has been reported by Bidelman (1962), and Pb has been identified in α^2CVn by Burbidge & Burbidge (1955).

Those Ap stars that have periodic magnetic fields also are spectrum variables; it is found that some spectral lines are constant in intensity while others vary with the same period as the magnetic field. There are, however, a few stars which show no correlation between spectrum variation and magnetic field variation (Babcock, 1958). Typically, one group of lines will increase in intensity while another group of lines decreases. In the stars α^2CVn and HD125248, the EuII and CrII lines vary in antiphase with one another; the EuII line is at maximum strength on HD125248 when the field has positive polarity, but reaches maximum strength on α^2CVn at negative polarity.

The spectrum variations are not at all easily explained. The oblique rotator model offers one possibility; some mechanism has caused elements to be more abundant on some parts of the star than on others, and as the star rotates, the different patches move in and out of the line of sight. On the other hand, the changing line intensities could also to some extent result from variations in temperature and pressure over the surface of the star.

Production of Anomalous Abundances

Two lines of thought have emerged with regard to possible causes of anomalous abundances. One suggestion is that the anomalies are only apparent ones, caused by some mechanism which enhances certain spectral lines and diminishes others. No specific mechanism has been proposed, however. Apparent overabundances could also be caused by some mechanism which caused certain elements to migrate to one region of the star. The migration of paramagnetic ions in a field gradient has been suggested by Jensen (1962) and Babcock (1963). Babcock has pointed out that Cr, Mn, and Eu all have large magnetic moments. However, this mechanism does not explain the overabundances of all the other elements; furthermore, to account for the magnitudes of the observed abundances would require extremely steep magnetic field gradients.

It is most likely that the abundance anomalies are real and have been caused by nuclear reactions in the star, either in the deep interior (followed by convective mixing) or on the surface. Burbidge and Burbidge (1955) suggested that the abundance anomalies were caused by surface nuclear reactions initiated by ions which had been accelerated by the magnetic field. This idea was considered by Fowler, Burbidge and Burbidge (1955) in somewhat more detail; they pointed out that reactions in which alphas, deuterons or neutrons were bombarding particles would lead to the build-up of heavy elements. However, on the basis of qualitative considerations, they convinced themselves that such a mechanism could not explain the observed overabundances, and so abandoned this model in favor of a considerably more complicated one (Fowler, Burbidge, Burbidge and Hoyle, 1965). They concluded that overabundances of the rare-earth elements coupled with a normal abundance of Ba can only be explained by a process of rapid neutron addition similar to that which occurs in a supernova explosion. They therefore proposed that the star has gone through a good part of its evolution and has evolved from the red giant stage <u>back</u> to the main sequence. The star has already developed a degenerate core. Helium burning produces ^{12}C; proton capture produces ^{13}C by $^{12}C(p,\gamma)^{13}N(\beta^{+})^{13}C$. The ^{13}C (α,n) reaction then represents a source of neutrons. Rapid mixing must take place to bring the affected material up to the surface. In addition, considerable surface spallation must occur to account for the underabundances of the light elements.

As evolutionary history so complicated is rather difficult to accept. Moreover, there is considerable evidence to show that Ap stars are true main sequence stars rather than evolved stars. Ap stars have been found in young clusters where there are also stars more luminous (and therefore more rapidly-evolving) than A stars, and these more luminous stars are still on the main sequence. Also, when an Ap star is part of a binary system, the companion appears to be a main-sequence star. It is our assumption that the Ap stars are not highly evolved objects, from which it follows that the abundance anomalies cannot be the result of nuclear reactions in the deep interior of the star.

We have therefore investigated the hypothesis that surface nuclear reactions represent the most significant mechanism for the production of anomalous abundances. We will adopt the original proposal of Burbidge and Burbidge (1955) that these reactions are the result of the bombardment of nuclei at the stellar surface by particles acclerated in the magnetic field. That mechanisms exist on stars leading to the acceleration of particles to high energies is amply demonstrated by the fact that cosmic rays are known to come from the sun with energies in the BeV region. By analogy with experimental measurements of cosmic ray energies, we will assume that the bombarding flux consists of protons and/or alphas which have an energy spectrum of the form

$$N(E) \sim E^{-n} \tag{1}$$

Where n, the spectral index, has been taken equal to 2.5 in most of this work.

Because of energy losses through ionization, a low-energy cutoff of this spectrum is to be expected, and we have generally assumed this to be at 1 MeV. In order for heavier elements to be built up, a significant part of the flux must be in the 1-50 MeV region. Above 50 MeV, breakdown reactions will be predominant.

Our calculation differs from that of Burbidge and Burbidge in that we have used considerably more detailed values of reaction cross sections. A method has been developed for calculating rapidly and accurately the cross sections for reactions in which one, two, or three particles are emitted following the capture by a target nucleus of a 1-40 MeV proton or alpha. The details of this method are discussed in the preceding paper. These cross sections have been substituted into a reaction network calculation in which the abundannces of approximately 300 nuclear species are followed as a function of the integrated bombarding flux of protons and/or alphas. In this manner we can determine whether or not large overabundances can be produced under reasonable physical conditions. It should be kept in mind, however, that the size of the computation necessitates the use of several simplifying assumptions; consequently the model used here represents only a rough approximation to the conditions at the surface of an Ap star.

Since the method of cross section calculation described in the preceding paper is based on statistical methods it is not expected to be very reliable for lighter nuclei. While we have obtained cross sections for such nuclei using this method, our principal interest has been in the medium and heavy nuclei. Hence our results for the lighter nuclei can be correct only in a qualitative sense, and they should be so regarded in the results to be presented later.

Reaction Rates

If a represents the bombarding particle and X is the target nucleus, then the reaction rate for a given interaction involving a and X is

$$r_{aX} = N_X \int N_a(\underset{\sim}{v})\, \sigma(\underset{\sim}{v})\underset{\sim}{v}d\underset{\sim}{v} \tag{2}$$

where N_X is the number of X nuclei/cm^3, $N_a(\underset{\sim}{v})$ is the velocity distribution of bombarding particles, and $\sigma(\underset{\sim}{v})$ is the cross section for the reaction of interest. r_{aX} is then the number of reactions/cm^3-sec. Since it is preferable to give cross sections in terms of energy, Equation (2) will be rewritten as follows:

$$r_{aX} = \left(\frac{2}{M}\right)^{\frac{1}{2}} N_X \int N_a(E)\sigma(E)^{\frac{1}{2}}\, dE \tag{3}$$

where the reduced mass $M = M_a M_X/(M_a + M_X)$.

In accordance with Equation (1), we assume a energy distribution for the bombarding particles of the form

$$N_a(E) = \begin{cases} A_n E^{-n}, & E \geq E_o \\ 0 & , E < E_o \end{cases} \tag{4}$$

where E_o is the low-energy cutoff, and A_n is a suitable normalization factor.

The spectrum can be normalized in several ways. In our calculations, we have stipulated that the total energy density is a fixed quantity. That is, whatever the mechanism involved in accelerating the bombarding particles, it can supply only a fixed amount of energy to be distributed among the particles. The energy density D_E is defined as

$$D_E = \int E N_a(E) dE \tag{5}$$

Substituting Equation (4) into the above yields

$$A_n = (n-2) E_o^{n-2} D_E \quad ,$$

so that to insure a finite energy density we must have $n > 2$.

If it is desired to normalize on the basis of a fixed number N_o of particles/cm^3, one obtains

$$N_o = \int N_a(E) dE = \frac{A_n}{(n-1) E_o^{n-1}} = \frac{(n-2) D_E}{(n-1) E_o} \tag{6}$$

The simple relationship between N_o and D_E facilitates a change from one normalization to the other.

Assuming a fixed energy density D_E, the expression for the reaction rate, Equation (3), then becomes

(7) $$r_{aX} = \left(\frac{2}{M}\right)^{\frac{1}{2}} (n-2) E_o^{\,n-2}\, D_E N_X \int_{E_o}^{\infty} E^{-(n-\frac{1}{2})}\, \sigma(E)\, dE$$

There are two types of cross sections which are required for the calculation. The first type, which we denote as $\sigma_X(E)$, is the total reaction cross section and is used to calculate the rate of destruction of nuclide X. The second type is represented by $\sigma_{XY}(E)$, and represents the total cross section for all reactions which lead to the formation of nuclide X as a result of the bombardment of Y. Cross sections of the latter type thereby contribute to the rate of formation of X. To simplify the notation, we define the quantities

(8) $$J_X = \left(\frac{2}{M}\right)^{\frac{1}{2}} (n-2) E_o^{\,n-2} \int_{E_o}^{\infty} E^{-(n-\frac{1}{2})} \sigma_X(E)\, dE$$

$$J_{XY} = \left(\frac{2}{M}\right)^{\frac{1}{2}} (n-2) E_o^{\,n-2} \int_{E_o}^{\infty} E^{-(n-\frac{1}{2})}\, \sigma_{XY}(E)\, dE$$

Following Equation (7), the rate of destruction of X is given by

(9a) $$r_X = D_E J_X N_X$$

and the rate of formation of X from Y is

(9b) $$r_{XY} = D_E J_{XY} N_Y$$

Therefore the time rate of change of the abundance of element X is

(10) $$\frac{dN_X}{dt} = D_E \left[\sum_Y (J_{XY} N_Y) - J_X N_X \right]$$

Since it is customary to give element abundances in terms of the silicon abundance, we define the relative abundance $n_X = N_X/N_{Si}$, where N_{Si} is the abundance of silicon at t = 0. We also define the parameter

$$w = D_E t \tag{11}$$

so that Equation (10) reduces to

$$\frac{dn_X}{dw} = \sum_Y J_{XY} n_Y - J_X n_X \tag{12}$$

The Reaction Network

We are now in a position to solve a set of simultaneous differential equations of the form of Equation (12) so as to follow the changes in abundance of all nuclear species of interest. We have chosen to include all the stable isotopes plus those unstable isotopes with half-lives greater than 10^6 years. That is, it is assumed that the reactions proceed at a rate slow enough so that unstable nuclei with half-lives less than 10^6 years will decay before capturing an incident particle. We have selected 10^6 yrs. as a cutoff point mainly to keep the network within a reasonable size, and also because 10^6 yrs. approaches the time spent on the main sequence by an A star. Based on this cutoff, the network includes 293 nuclear species.

We solved the network equations for three cases: a bombarding flux of protons only, a flux of alphas only, and a flux composed of equal numbers of protons and alphas. We do not consider any secondary reactions initiated by the emitted particles; it is assumed that these particles are scattered down to low energies by collisions with hydrogen atoms. The low energy cutoff E_o is taken to be 1 MeV, and several values of the spectral index n from 2.5 to 8 were considered. The initial abundances are those tabulated by Cameron (1963).

Results

We have found that bombardment of the nuclei in an initial solar abundance distribution by a pure proton flux leads to a continuing loss of nucleons and hence to a progressive break-down into hydrogen and helium. We did not follow changes in the hydrogen and helium themselves. We present the results with all nuclei of the same charge number summed together to facilitate comparison with observations.

The changes in the initial abundance distribution produced by progressively larger integrated fluxes of protons are shown (for $Z \leq 50$) in Figures 1 and 2. For smaller integrated fluxes the most striking effect is the depletion of Fe, Co, and Ni and the enhancement of elements between Ca and Fe. There is also a depletion of the abundances of even-Z medium elements and an enhancement of the abundances of odd-Z medium elements. If only a portion of the stellar surface were so bombarded, the principal spectroscopic changes that would be observed would be an increase in those elements with the larger enhancement factors. However, a continued proton bombardment leads to a progressive depletion of all the medium and heavy element abundances.

On the other hand, bombardment by a flux of pure alpha-particles leads to a build-up toward heavier elements. Reactions of the type (α,n), (α,p), $(\alpha,2n)$, (α,pn), and $(\alpha,3n)$ contribute to a predominance of nucleon-addition processes. Only at high charge numbers, where Coulomb barriers are higher and only the more energetic reactions can take place, are the nucleon additive processes partially compensated by nucleon subtractive processes such as $(\alpha,\alpha n)$ and $(\alpha,\alpha 2n)$. Hence after a very extended bombardment the abundance distribution tends to stabilize in the heavy element region.

Details of this are shown in Figures 3 and 4. In Figure 3 the curve corresponding to $w = 10^{12}$ has a depletion of elements with $Z < 16$ and an enhancement of elements in the range $16 < Z < 50$. At $w = 5 \times 10^{12}$ there is a depletion of elements with $Z < 35$ and an enhancement of elements with $35 < Z < 75$. It may be seen in Figure 4 that further bombardment enhances the region from the rare earths up to bismuth, with a very sharp cutoff at and below the closed shell of 82 neutrons. The lighter nuclei at this closed shell are isotopes of xenon and barium. At later stages of bombardment, the elemental abundances increase by several orders of magnitude along the closed shell from barium, which is normal in abundance, to samarium. This distribution thus reproduces qualitatively the Ap abundance anomaly in which large overabundance factors occur only above barium in the rare earth region.

It was also found that when a bombardment was carried out with equal fluxes of protons and alphas, the destructive effect of the protons predominated, owing to their larger reaction cross sections.

Many of these features are very suggestive in terms of the Ap anomalies. Presumably the abundance changes on the surface of an Ap star represent the superposition of a wide variety of bombarding fluxes. Substantial depletions of elements, particularly the lighter elements, can be produced by a general bombardment of the surface by relatively small integrated fluxes of either protons and alphas. However, the distinctive enhancements can only be produced by the alpha bombardments. Since many of the enhancement factors are much greater than those observed, it appears that small portions of the surface must be exposed to medium and large integrated alpha fluxes.

Figure 5 shows the abundances of Si, Sc, Ca, and Ti as a function of bombarding flux. The silicon enhancement is obtained for rather small fluxes, and this may be the characteristic feature of the silicon Ap stars. But elements such as Sc should then be more enhanced than Si; however, this is not noticeable in Table 1. We have not run enough cases with mixed bombardment by protons and alphas to determine whether significant enhancements of Si are possible without larger enhancements of Sc.

Figure 6 shows the variations in the abundances of Cr, Mn, and Fe. It can be seen that Cr and Mn show larger relative increases in abundance than does Fe; this result is in agreement with observations.

The most interesting result, however, is concerned with the rare earth abundances, shown in Figure 7. Not only do we find that large overabundance ratios are produced for these elements, but also that the overabundances will be maintained at a high level for a long time. We note a change in the shape of the abundance curves, beginning with Ba, indicating that a near-equilibrium has been established between production and destruction rates leading to a relatively constant abundance. This quasi-equilibrium abundance is greater than the initial abundance at and above Pr.

The reaction rates will decrease with increasing Z as a consequence of the increasing Coulomb barrier of the target nucleus and the inverse power-law energy spectrum (Equation 1) of the incident alphas. We find that as the rare-earth elements are reached, the rate of production resulting from the feedback of $(\alpha,\alpha n)$ and $(\alpha,\alpha 2n)$ becomes sufficient to maintain a nearly stable abundance.

The shape of the alpha energy spectrum is significant in that higher values of the spectral index n will result in much lower rates for the higher energy reactions in which 2 or 3 particles are emitted, so that the feedback from $(\alpha,\alpha n)$ and $(\alpha,\alpha 2n)$ reactions becomes less significant. The results described here correspond to a value of $n = 2.5$, and represent the best agreement with observations over the range of n (from 2.5 to 8) for which results were obtained.

A Model for the Production of Abundance Anomalies

It has been demonstrated that if one takes a gas having a cosmic abundance distribution and bombards it with alpha-particles distributed over an inverse power-law energy spectrum in the 1 - 40 MeV range, large overabundances will be produced for those elements found to be greatly overabundant in Ap stars. It remains to be seen whether these results can be related to actual physical conditions in these stars.

In Table 2 we have listed the maximum overabundances obtained in the calculation for several elements of interest; these are compared with the observed overabundances in Ap stars. It is seen that the calculated overabundances exceed the observed ratios by several orders of magnitude. Consequently, it is not necessary for particle bombardment to occur over the entire surface of the star; no more than 1% of the total surface need be involved. It is well known that sun spots are regions of magnetic activity where particles can be accelerated to high energies. We thus assume that extensive particle bombardment takes place only in small areas on Ap stars. At solar maximum, approximately 2% of the sun's surface is covered over with spots. Irradiation of a similar fraction of the surface area on Ap stars would be sufficient to produce the observed overabundance factors. Furthermore, magnetic fields in sun spots are of the order of 10^3 times greater than the average for the entire sun. If the same ratio applies to Ap stars, we could then expect to find magnetic fields of $\sim 10^6$ gauss in such areas. The energy density of such a field would be $H^2/8\pi \approx 4\times10^{10}$ erg/cm^3.

The upper limit on the size of the magnetic field that can be contained within a stellar interior is given by the condition that the magnetic field energy should not exceed the released gravitational potential energy, or

$$\frac{H^2}{8\pi} \cdot \frac{4\pi}{3} R^3 < \frac{3}{2} \frac{GM^2}{R} \quad .$$

If, for an A star we choose a mass and radius 3.5 and 2.5 times those of the sun (Allen, 1963), then $H < 1.8\times10^8$ gauss. The postulated magnetic field is only 10^{-2} of this limit, and the corresponding energy density throughout the star would only be 10^{-4} of that which could be contained. Hence the postulated magnetic field could represent a flux tube rooted in the deep interior of the star which projects through the surface.

Assuming the existence of such a field, we can determine whether the energy requirements necessary to produce overabundances can be met. From Table 2, we note that $w = D_E t$ becomes of the order of 10^{13} erg-sec/cm^3 in the region of the maximum overabundances. A particle energy density of 10^{10} erg/cm^3 would then require an irradiation time of 10^3 sec. Alternatively, we can consider the situation on the basis of a fixed particle number density N_o. According to Equation (6), if $n = 2.5$ and $E_o = 1$ MeV $= 1.6 \times 10^{-6}$ ergs,

$$N_o = 2.08 \times 10^5 \, D_E \tag{13}$$

Assuming a particle density of 10^{12} alphas/cm^3 (i.e., 1% of the helium atoms in the atmosphere are accelerated at any instant), we obtain an energy density of approximately 5×10^6 ergs/cm^3, which corresponds to a total irradiation time of 5×10^6 sec. Such a time scale is comparable to that observed for the lifetime of sun spots.

A further requirement is that the magnetic energy in the flux tube where the particle acceleration takes place should be more than sufficient to supply this energy density of accelerated particles. Since the stellar radius is $\gtrsim 10^{11}$ cm, the length of the flux tube above the surface may well be $\gtrsim 10^9$ cm. Let us suppose that the above particles are accelerated well above the photosphere and pass down the flux tube until absorbed below the photosphere. Then

$$wv < \frac{H^2}{8\pi} L$$

where w is the time-integrated energy density of alpha-particles required to produce the rare earth anomaly, v is the parallel velocity component of the particles, and L is the length of the flux tube in which energy is available for accelerating the particles. Taking $w \sim 10^{13}$, $v \sim 10^9$ cm/sec, and $L \sim 10^9$ cm, we find $H > 10^7$ gauss. This requirement can be relaxed if it is assumed that the lower energy cutoff on the alpha-particle spectrum is 10 MeV (which would not significantly alter the character of our results), and if it is assumed that the photospheric scale height is traversed by the alpha-particles several times (say 20). In this very efficient limit we still need $H > 10^6$ gauss. These limits are not inconsistent with our previous discussion.

It should be noted that the time scale assumed in the network calculations was 10^6 yrs, whereas 10^2 - 10^6 sec is more physically plausible. Consequently, one would expect many of the shorter-lived nuclides to build up appreciable abundances, and these nuclides should be included in the network (assuming a cutoff time of 10^4 sec would call for the addition of approximately 200 more nuclides to the network). With a larger network, one would then expect a redistribution of abundances among adjacent elements, but the overall effect would undoubtedly be the same. At any rate, the quantitative abundance ratios obtained in the present calculation represent at best a first approximation.

In this model, then, the growth of an area of high magnetic field strength on the surface of an Ap star results in the acceleration of alphas (but not protons) to MeV energies. Nuclear reactions are initiated at the surface, which result in large abundance changes within the region. Longer irradiation times will produce overabundances of the rare earth elements, whereas shorter times will produce abundance changes only as far as, for example, the elements in the vicinity of Fe. When the irradiation stops, the altered abundances are frozen in by the lack of large-scale convection in the star. The newly-formed abundances then remain near the surface and contribute to the integrated spectrum of the star.

The entire model hinges on the assumption that an adequate flux of MeV-range alphas will be produced at the surface. The most likely acceleration mechanism would appear to be hydromagnetic or plasma waves, in which a particle will be accelerated if its Larmor frequency is equal to the frequency of the waves. Since the Larmor frequency is dependent on e/m, there is a cut-off frequency below which alphas are accelerated and protons are not.

Such mechanisms are being studied by Melrose (1966) who is presently calculating the energy spectra produced by various acceleration mechanisms of this type. We expect to repeat the calculation, with a more detailed network, using these energy spectra; we hope that by attempting to make the network more closely representative of the physical conditions we can determine whether or not the abnormal abundances found in Ap stars are the result of surface nuclear reactions.

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Table 1 : Logarithmic Overabundance Ratios for Some Ap Stars (from Sargent, 1964)

Element	α^2CVn	HD 133029	HD 151199	βCrB	γEqu	3CenA	73Dra	53Tau	αCnc
He						−0.8			−1.2
Be	+1.2					<+0.4			+2.0
C						0.0		+0.4	
N						+0.7			
O	−1.0			<−1.8	<−1.7	−0.8			+0.3
Ne						0.0			
Na					0.0				
Mg	−0.4	+0.1	+0.1	+0.2	+1.2	−0.6	+2.7	−0.3	−0.8
Al	0.0	+0.3				<−0.2			
Si	+1.0	+1.4	+0.1		+0.5	+0.3	+0.7	+0.1	
P									+2.0
S						<−1.0			
A						+0.1			
Ca	−1.7	−1.3	+0.4	+0.1	+0.7	−0.4	−2.0	−1.5	
Sc	−0.2			+0.4	+0.7	<+0.6			
Ti	+0.4	+0.4		+0.9	+0.2	<+0.2	+0.3	+0.6	−0.2
V	+0.1	+0.5		+0.4	+0.8	<+0.7			
Cr	+0.7	+1.0	+0.3	+1.5	+1.3	<−1.0	+1.6	−0.9	+0.1
Mn	+1.2	+1.2	+1.0	+1.6	+1.8	+0.6	+1.5	+1.8	+1.5
Fe	+0.5	+0.6	+0.0	+0.8	+0.6	+0.6	+0.6	−0.3	−0.3
Co				+1.0	+1.7				
Ni	+0.5	+0.4		+0.3	+1.6	−0.2			
Ga						+3.8		+2.4	
Kr						+3.1			
Sr	+1.1	+1.2	+1.8	+1.6	+2.6	<+1.7	+0.9	+1.5	
Y	+1.3				+0.6				
Zr	+1.5	+1.6		+2.0	+0.8				
Ba	≤0.0		−0.2	+0.7	+1.2				
La	+3.0	+2.3		+2.8	+2.3				
Ce	+2.6	+2.4		+2.9	+2.0		+1.3		
Pr	+3.0	+2.8		+2.7	+2.4				
Nd	+2.4	+2.1		+2.2	+2.3				
Sm	+2.6	+2.4		+2.3	+1.7				
Eu	+3.3	+2.9	+2.1	+3.2	+2.6		+3.3		
Gd	+2.9	+2.5		+2.9	+2.2		+2.8		
Dy	+2.9	+2.7		+3.6	+2.5				
Hg									+4.6
Pb		+3.2							

Table 2: Calculated Maximum Overabundance Factors for Alpha Bombardment and Comparison with Average Observed Overabundances in Ap Stars.

Element	Average Observed $\log A_{max}/A_o$	Calculated $\log A_{max}/A_o$	w at Maximum (10^{12} erg-sec/cm^3)
Si	0.6	1.0	0.2
Ca	-0.7	2.1	0.5
Sc	0.4	5.1	0.6
Ti	0.4	4.6	0.6
Cr	1.0	2.8	0.7
Mn	1.4	3.0	0.8
Fe	0.5	1.0	0.9
Ga	3.0	5.1	1.3
Kr	3.0	5.7	1.7
Sr	1.5	5.7	1.8
Y	1.0	6.0	1.8
Zr	1.5	5.4	1.9
Ba	0.5	6.5	4.5
Rare earths	2.5	7.0	5.0

Figure Captions

Figure 1 : Effect of proton bombardment on cosmic abundances (w in $erg\text{-}sec/cm^3$).

Figure 2 : Effect of proton bombardment on cosmic abundances (w in $erg\text{-}sec/cm^3$).

Figure 3 : Effect of alpha bombardment on cosmic abundances (w in $erg\text{-}sec/cm^3$).

Figure 4 : Effect of alpha bombardment on cosmic abundances (w in $erg\text{-}sec/cm^3$).

Figure 5 : Relative abundances of Si, Ca, Sc and Ti as a function of alpha bombardment.

Figure 6 : Relative abundances of Cr, Mn, and Fe as a function of alpha bombardment.

Figure 7 : Relative abundances of rare-earth region elements as a function of alpha bombardment.

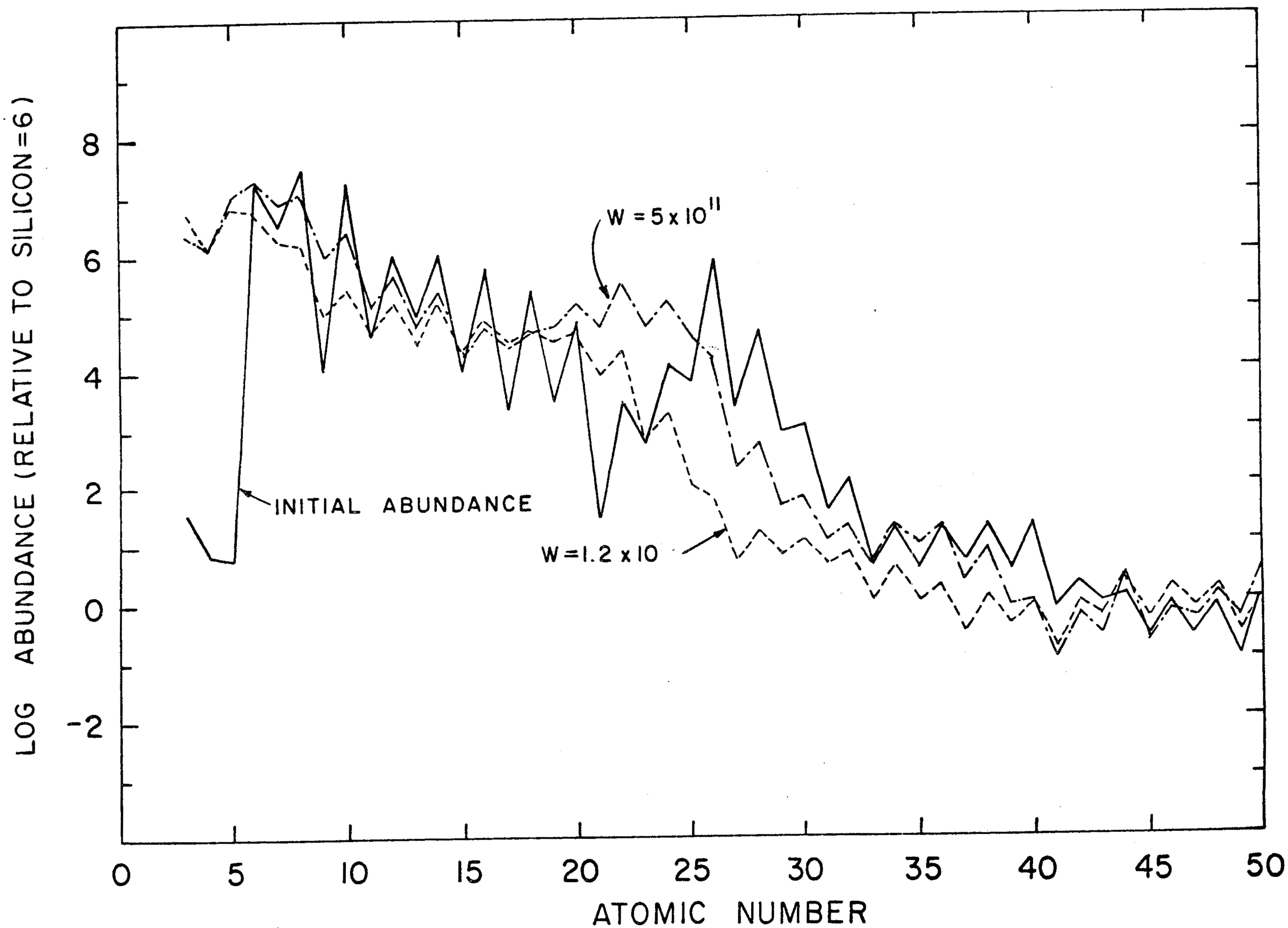

LOG ABUNDANCE (RELATIVE TO SILICON=6)
8
6
4
2
0
-2
W = 5 x 10^11
INITIAL ABUNDANCE
W = 1.2 x 10
0
5
10
15
20
25
30
35
40
45
50
ATOMIC NUMBER

Figure 1

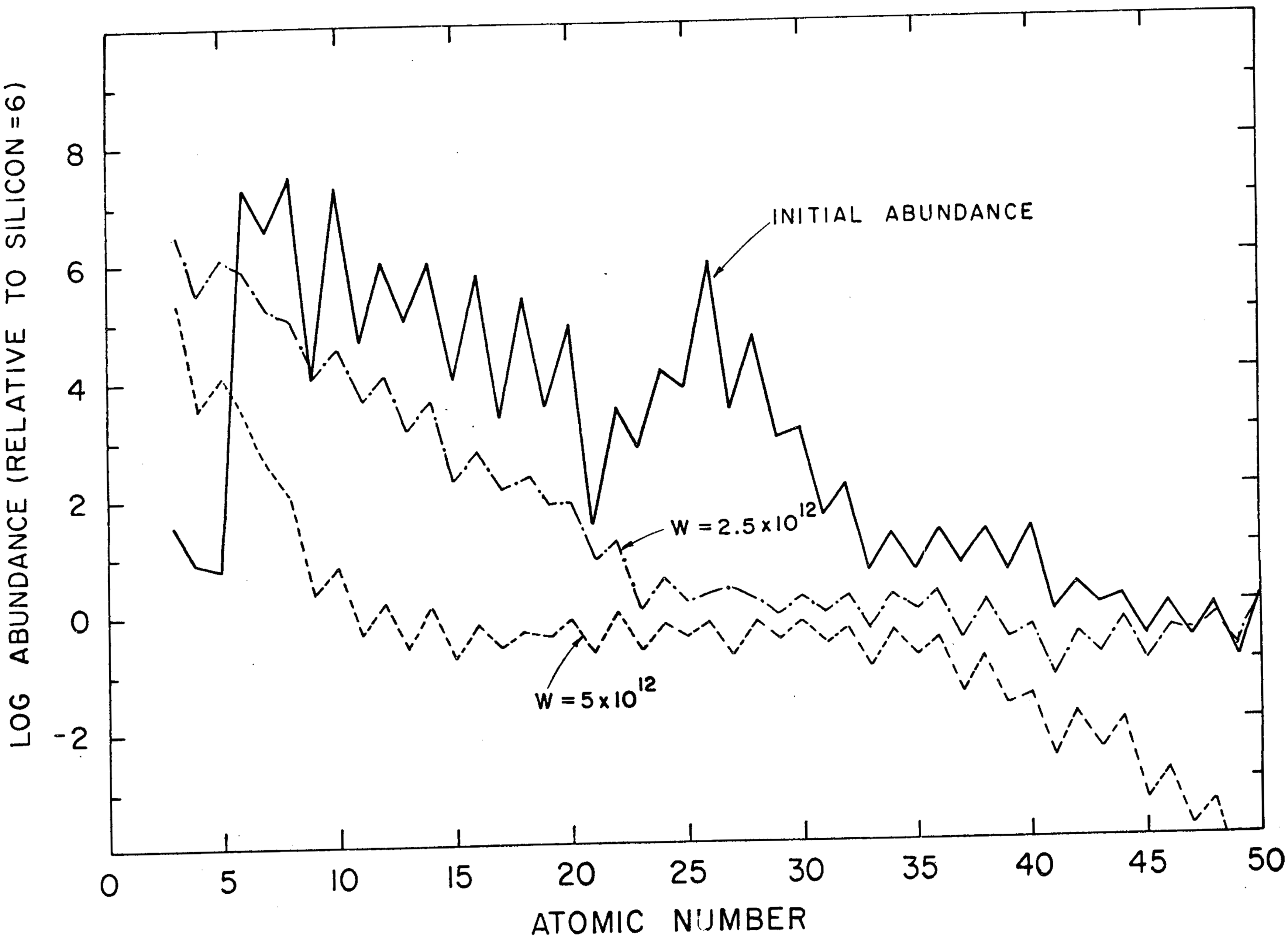
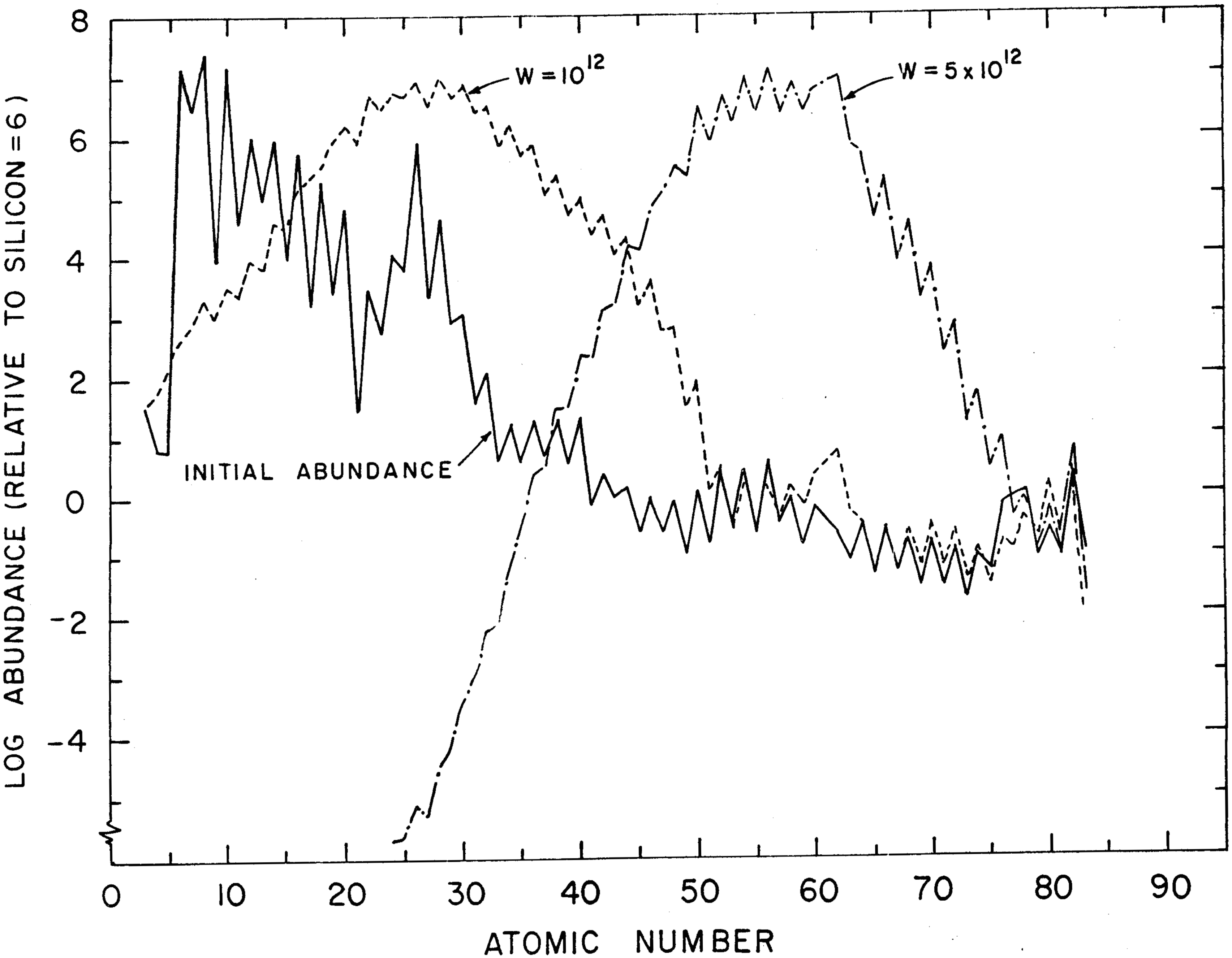
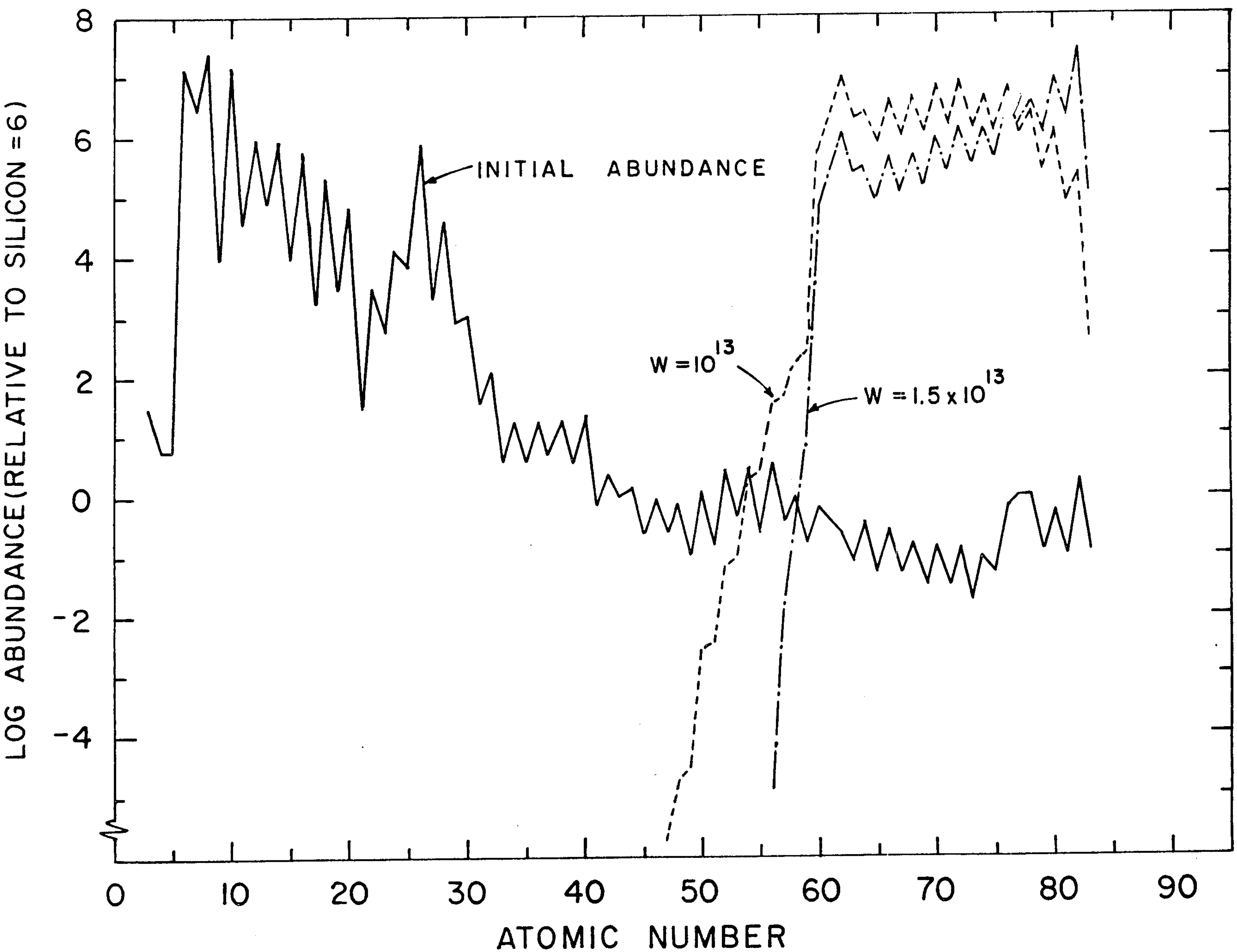

LOG ABUNDANCE (RELATIVE TO SILICON = 6)
8
6
4
2
0
-2
INITIAL ABUNDANCE
W = 2.5 x 10^12
W = 5 x 10^12
0
5
10
15
20
25
30
35
40
45
50
ATOMIC NUMBER

Figure 2



LOG ABUNDANCE (RELATIVE TO SILICON = 6)
8
6
4
2
0
-2
-4
$W = 10^{12}$
$W = 5 \times 10^{12}$
INITIAL ABUNDANCE
0
10
20
30
40
50
60
70
80
90
ATOMIC NUMBER

Figure 3



LOG ABUNDANCE(RELATIVE TO SILICON =6)
8
6
4
2
0
-2
-4
INITIAL ABUNDANCE
W =10^13
W = 1.5 x 10^13
0
10
20
30
40
50
60
70
80
90
ATOMIC NUMBER

Figure 4

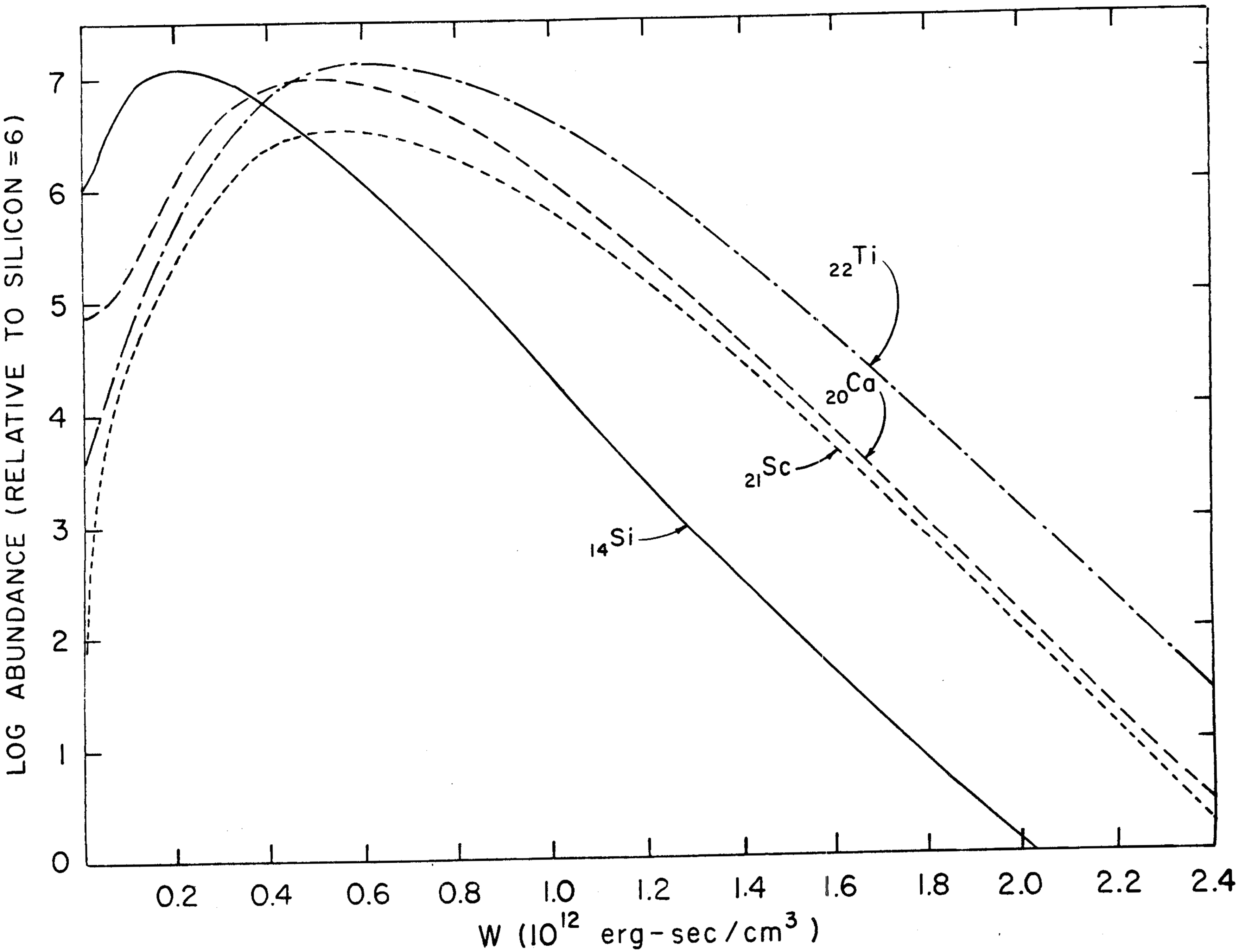

LOG ABUNDANCE (RELATIVE TO SILICON = 6)
0
1
2
3
4
5
6
7
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
W (10^{12} erg-sec/cm^3)
$_{22}$Ti
$_{20}$Ca
$_{21}$Sc
$_{14}$Si

Figure 5

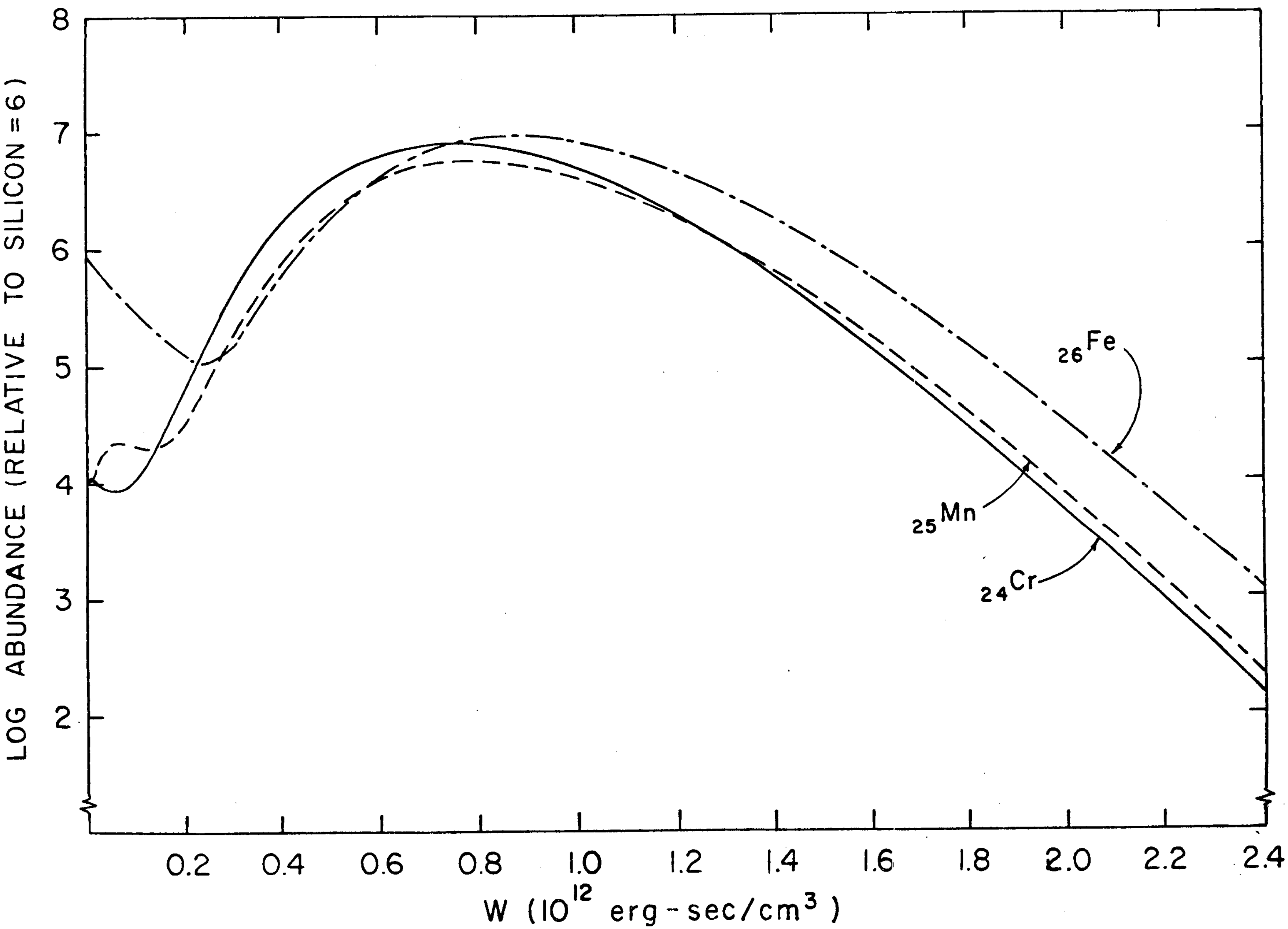

LOG ABUNDANCE (RELATIVE TO SILICON = 6)
8
7
6
5
4
3
2
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
W (10^{12} erg - sec/cm^3)
$_{26}$Fe
$_{25}$Mn
$_{24}$Cr

Figure 6

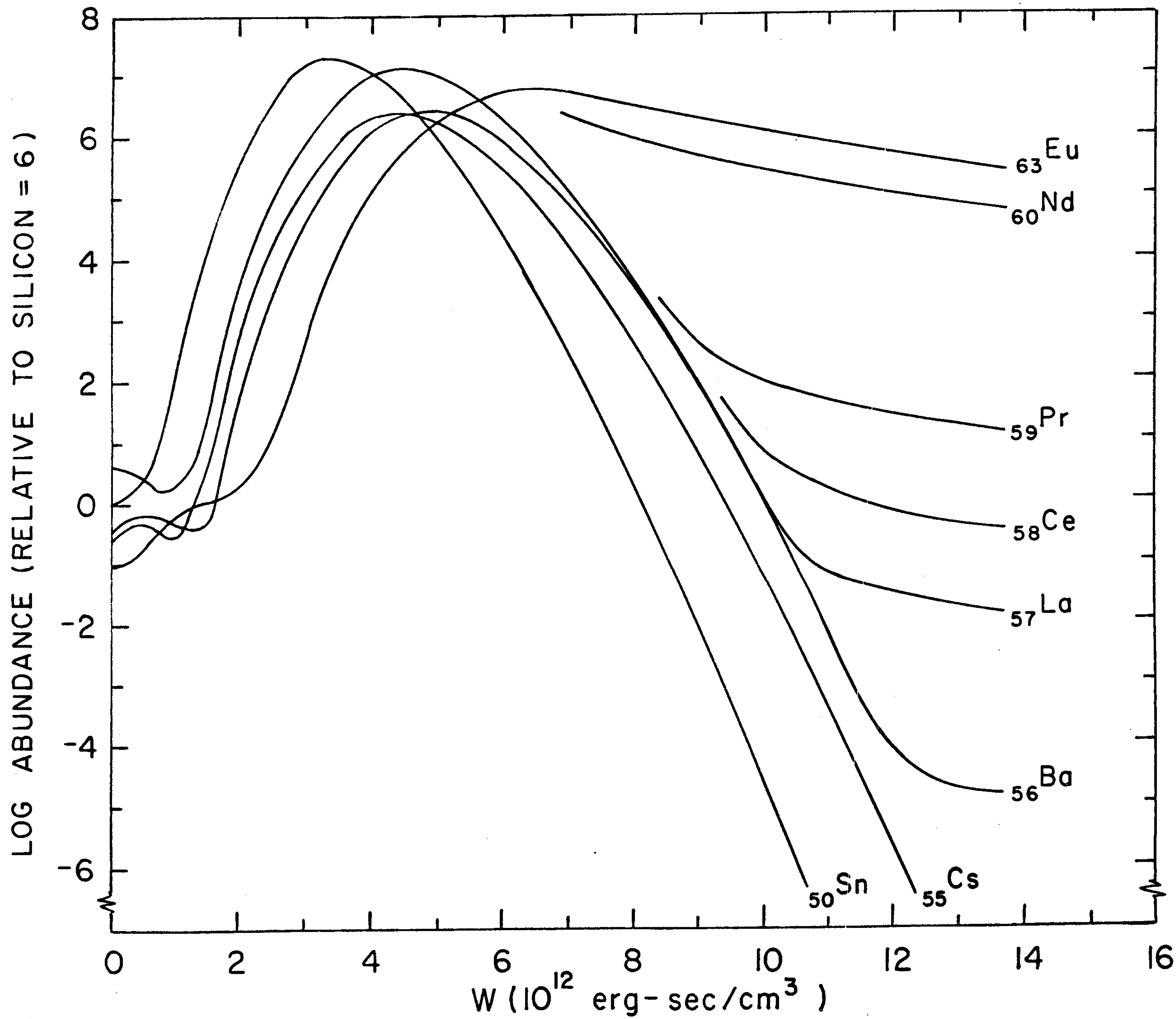

LOG ABUNDANCE (RELATIVE TO SILICON = 6)
8
6
4
2
0
-2
-4
-6
0
2
4
6
8
10
12
14
16
W (10^12 erg-sec/cm^3)
63Eu
60Nd
59Pr
58Ce
57La
56Ba
50Sn
55Cs

Figure 7